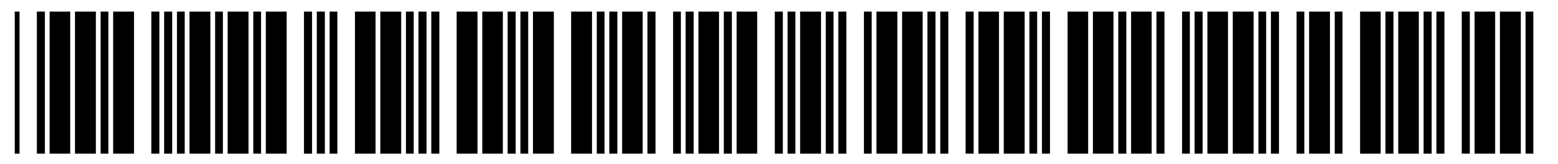

United States Patent [19]

Disney

[11] **Patent Number: 6,127,701**

[45] **Date of Patent: Oct. 3, 2000**

[54] **VERTICAL POWER DEVICE WITH INTEGRATED CONTROL CIRCUITRY**

[75] Inventor: **Donald Ray Disney**, Kokomo, Ind.

[73] Assignee: **Delco Electronics Corporation**, Kokomo, Ind.

[21] Appl. No.: **09/286,319**

[22] Filed: **Apr. 5, 1999**

Related U.S. Application Data

[62] Division of application No. 08/999,796, Oct. 3, 1997, Pat. No. 5,994,188.

[51] **Int. Cl.**[7] **H01L 29/76**

[52] **U.S. Cl.** **257/338**; 257/327; 257/350; 257/67

[58] **Field of Search** 438/268, 273, 438/269; 257/329, 327, 328, 337, 338, 335, 340, 341, 67, 69, 350

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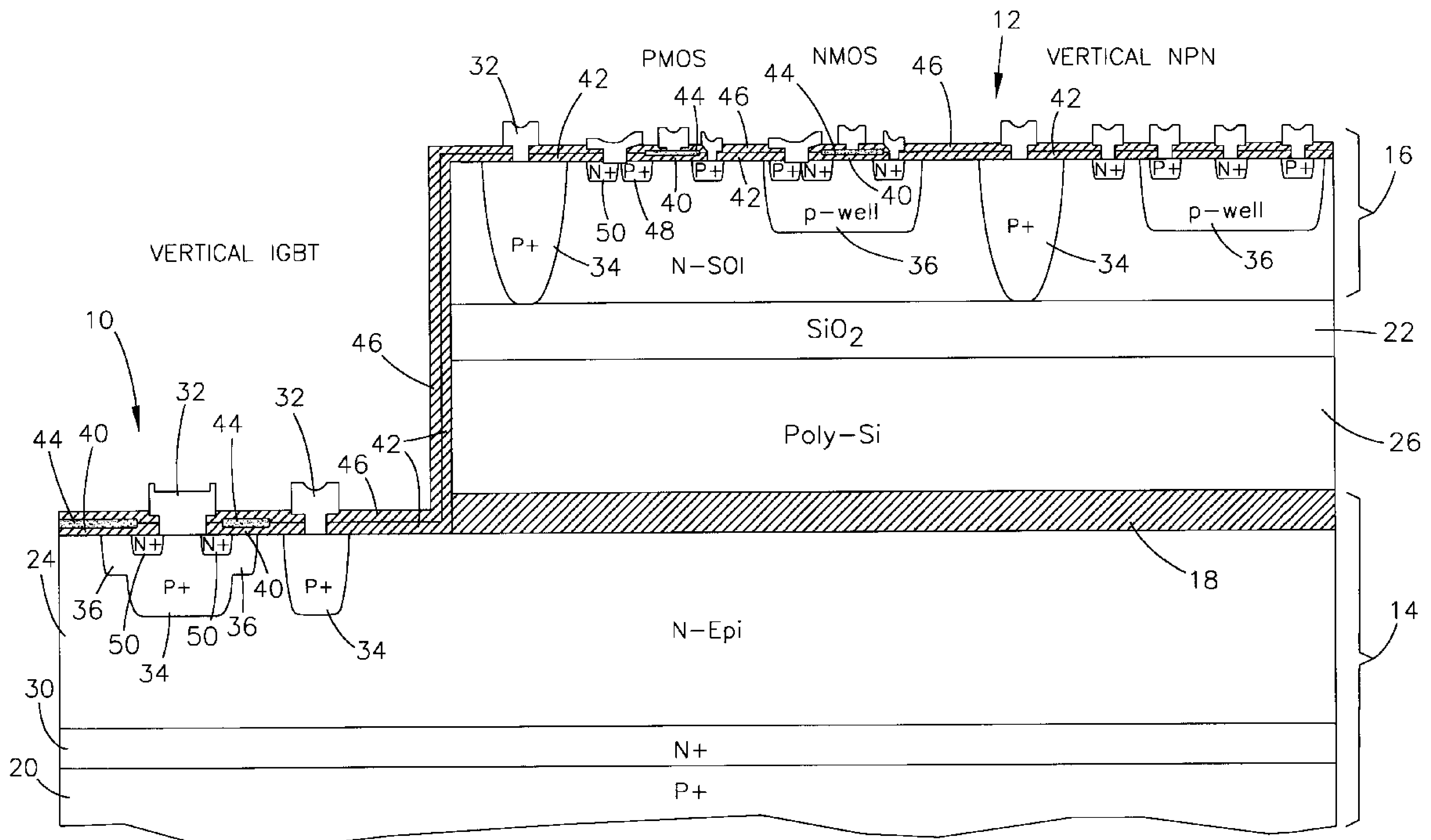
Primary Examiner—Michael Trinh
Attorney, Agent, or Firm—Jimmy L. Funke

[57] **ABSTRACT**

A process for integrating a vertical power device, such as an IGBT device, with suitable control circuitry, such as circuitry that provides self-protection from over-temperature (OT), over-voltage (OV) and over-current (OC) conditions. The process yields a vertical power device that is monolithically integrated with, and dielectrically isolated from, its control circuitry with the use of wafer-bonded silicon-on-insulator (SOI) material that yields a buried oxide layer. The process includes simultaneous fabrication of the power device below the buried oxide layer and its control circuitry above the buried oxide layer, in the SOI layer.

5 Claims, 3 Drawing Sheets



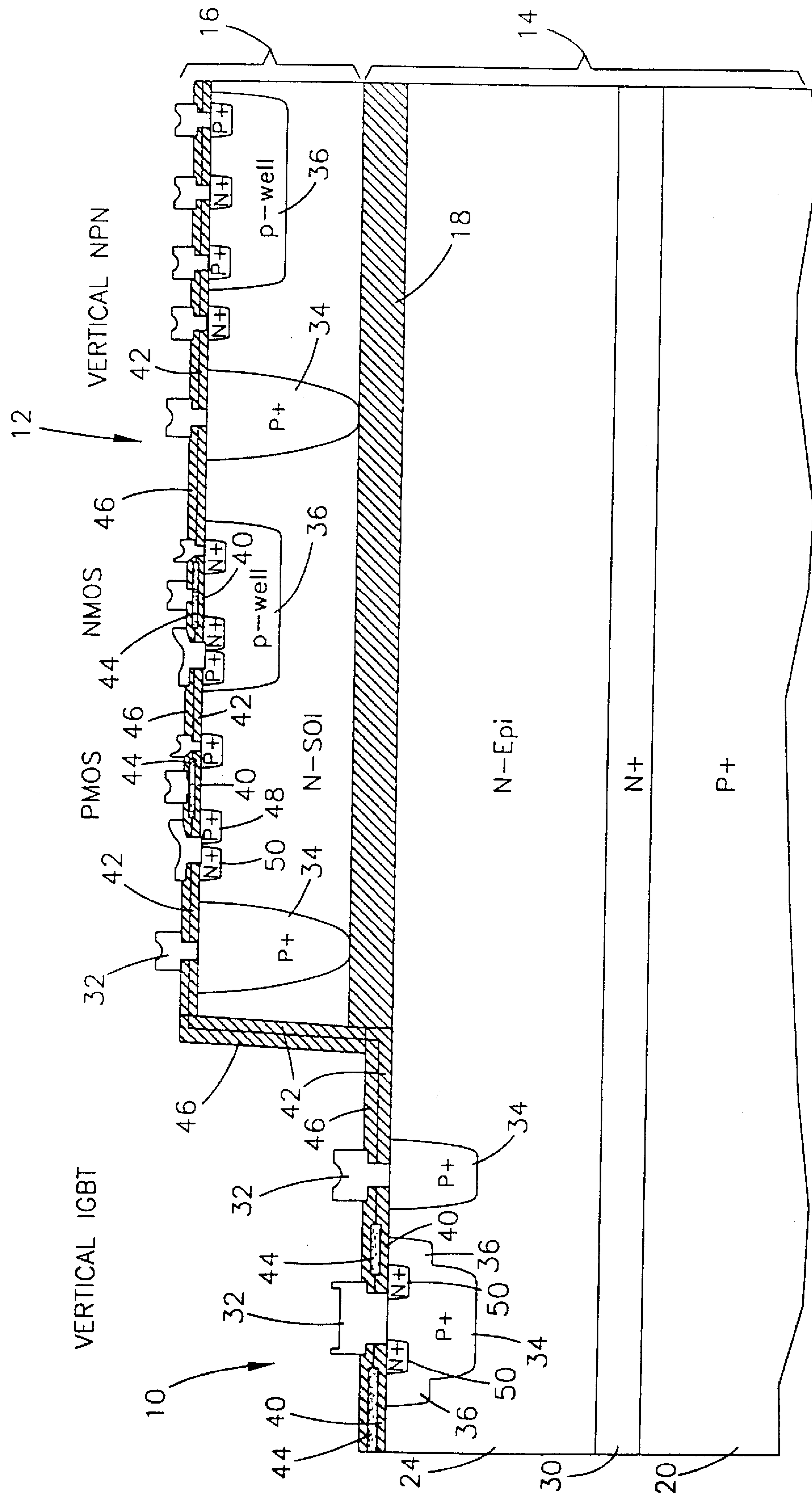


FIG. 1

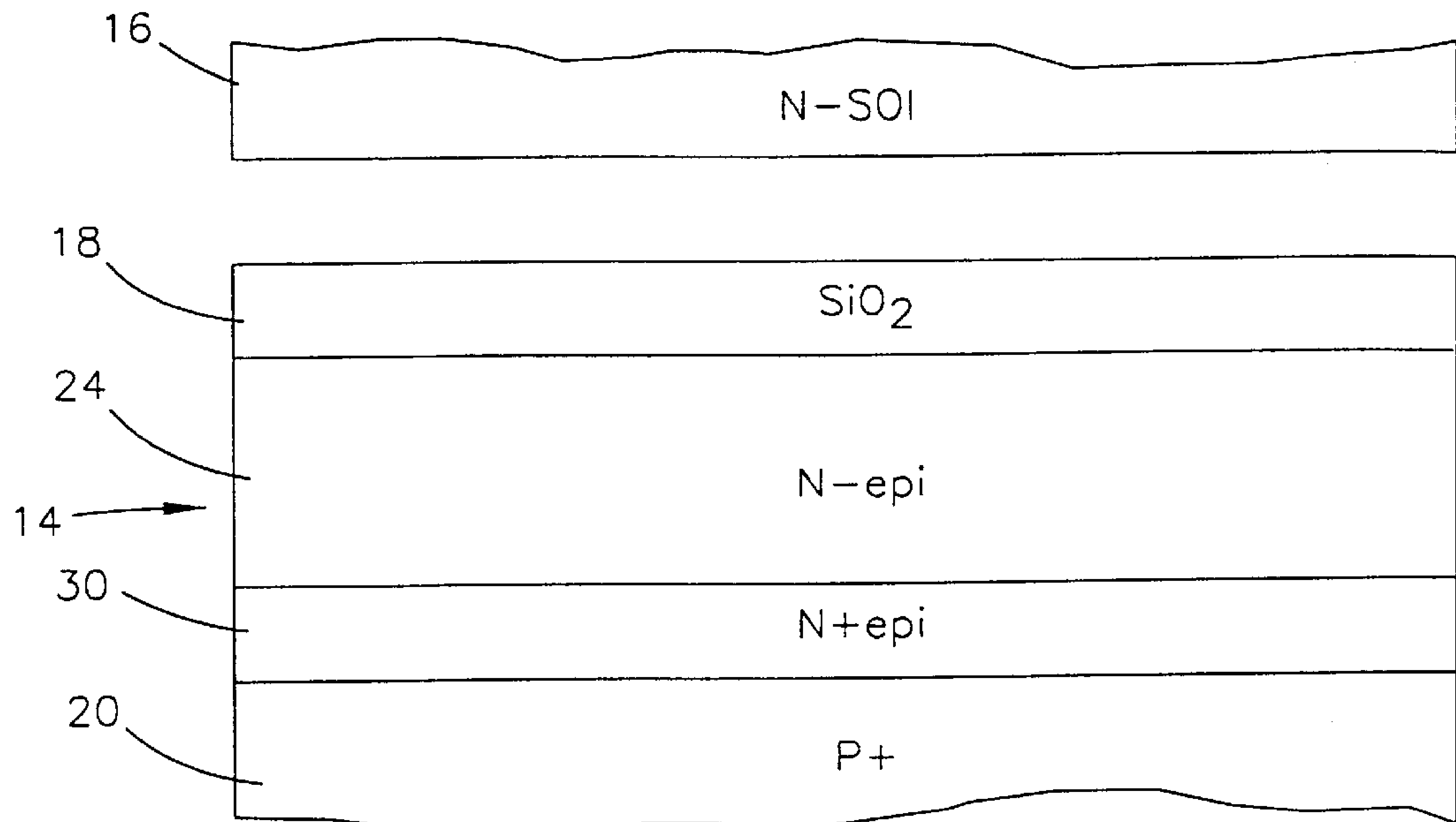


FIG.2

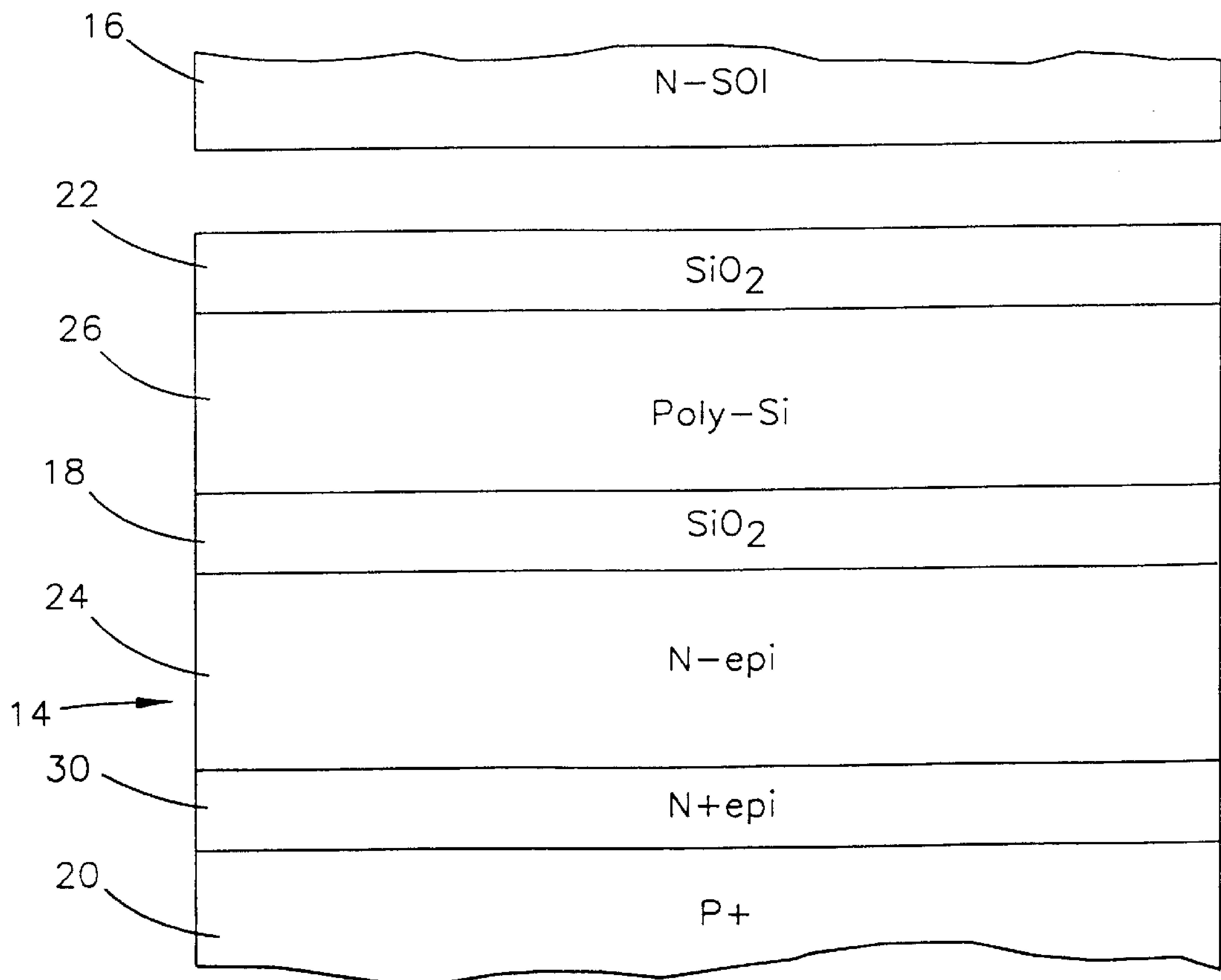
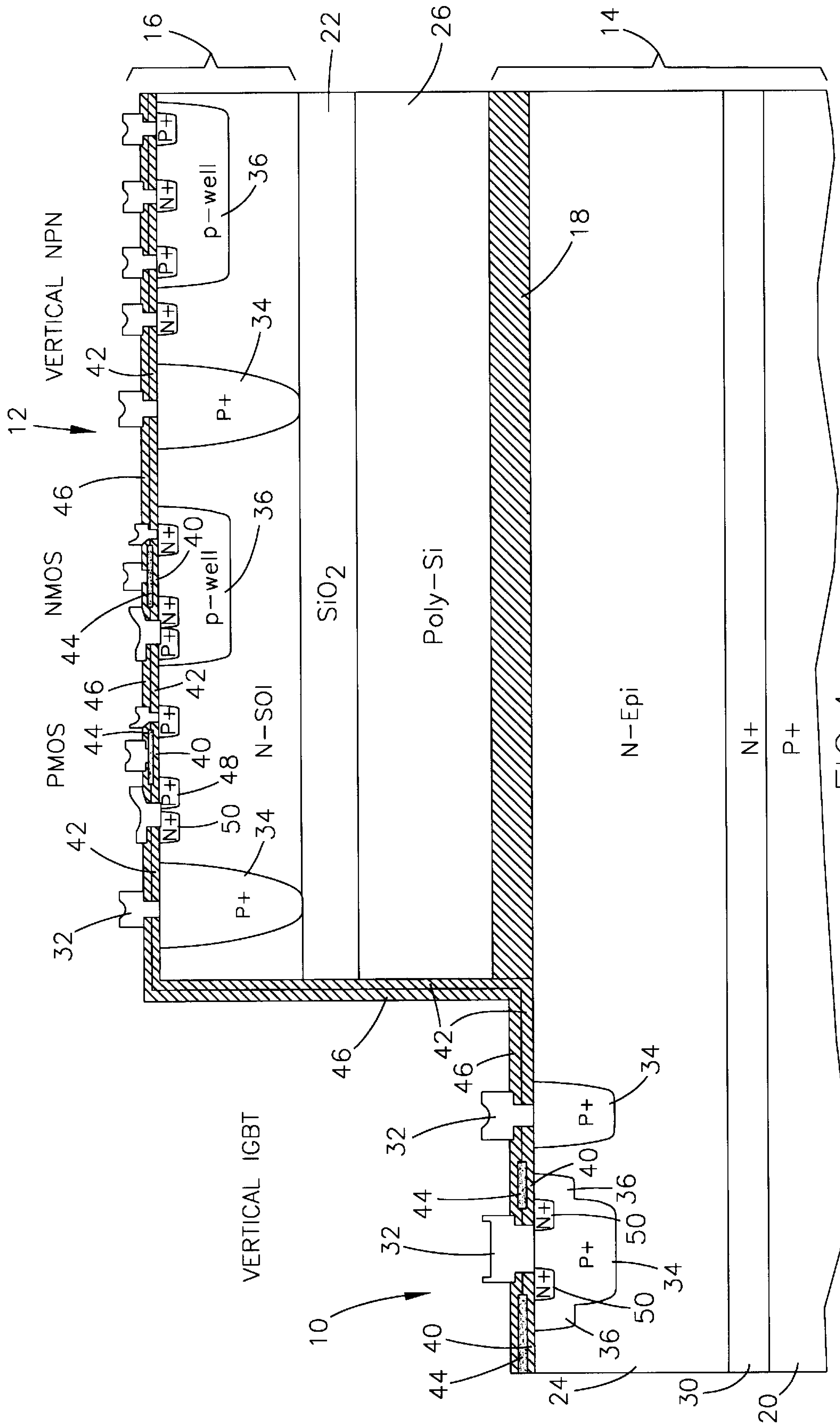


FIG.3


VERTICAL NPN
NMOS
PMOS
VERTICAL IGBT
p-well
N-SOI
SiO2
Poly-Si
N-Epi
N+
P+
FIG. 4

VERTICAL POWER DEVICE WITH INTEGRATED CONTROL CIRCUITRY

This is a division of application Ser. No. 08/999,796 filed on Oct. 3, 1997, now U.S. Pat. No. 5,994,188.

FIELD OF THE INVENTION

The present invention generally relates to semiconductor devices and processes for their fabrication. More particularly, this invention relates to a vertical power semiconductor device that is monolithically integrated with, and dielectrically isolated from, logic and control circuitry for the device with the use of a silicon-on-insulator layer.

BACKGROUND OF THE INVENTION

The demand for high-voltage insulated-gate bipolar transistor (IGBT) devices for automotive electronics applications has increased dramatically, particularly for such applications as coil drivers for ignition systems and motor drivers for electric vehicles. Accompanying this increased demand is a desire for "smart" IGBT devices, i.e., IGBT devices that are monolithically integrated with control circuitry to provide self-protection from over-temperature (OT), over-voltage (OV) and over-current (OC) conditions. However, full integration of an IGBT device with its control circuitry is complicated by the high voltages at which IGBT devices must operate, often about 400 to 1400 volts, and because the level of minority carriers present with IGBT devices would interfere with the low-voltage control circuitry.

Several techniques have been suggested by which various electronic power devices can be integrated with suitable control circuitry. For example, relatively low-voltage (40 to 100 volts) vertical DMOS (double-diffused metal-oxide semiconductor) devices are commercially available that rely on junction-isolation (JI) to provide electrical insulation for their control circuitry. However, junction-isolation cannot adequately protect control circuitry from the minority carriers inherent with IGBT devices. Silicon-on-insulator (SOI) technologies, such as wafer-bonding and separation by implantation of oxygen (SIMOX), have been employed in the fabrication of DMOS devices to achieve dielectric-isolation (DI), a viable isolation technique for use with high-voltage IGBT devices. However, such techniques have proven to be costly and/or yield devices characterized by inadequate performance or reliability. The use of polysilicon thin-film transistors for the control circuitry of DMOS devices has also enabled the implementation of dielectric-isolation. However, a shortcoming of this approach is that the performance of polysilicon transistors is inferior to equivalent single-crystal devices. Similar efforts to achieve dielectric-isolation with polysilicon structures for high-voltage IGBT devices have generally incurred relatively high processing costs.

In view of the above, it would be desirable if a process were available that would enable the monolithic integration of an IGBT device with suitable control circuitry, in which the resulting device is characterized by effective isolation of the control circuitry at high operating voltages, high performance, and relatively low processing costs.

SUMMARY OF THE INVENTION

It is an object of this invention to provide a high-voltage semiconductor power device that is monolithically integrated with control circuitry that protects the device from adverse operating conditions.

It is another object of this invention to provide a process for the fabrication of such a device, in which novel techniques are combined with relatively standard processing methods in such a way as to achieve dielectric-isolation of the control circuitry from the device.

It is a further object of this invention that such a process is particularly well suited for fabricating IGBT devices having operating voltages of about 400 to 1400 volts.

In accordance with a preferred embodiment of this invention, these and other objects and advantages are accomplished as follows.

According to the present invention, there is provided a process for Integrating a vertical power device, such as an IGBT device, with suitable control circuitry, such as circuitry that provides self-protection from over-temperature (OT), over-voltage (OV) and over-current (OC) conditions. The process uniquely yields a vertical power device that is monolithically integrated with, and dielectrically isolated from, its control circuitry with the use of wafer-bonded silicon-on-insulator (SOI) material that yields a buried oxide layer. The process includes simultaneous fabrication of the power device below the buried oxide layer and its control circuitry above the buried oxide layer, in the SOI layer.

Generally, the process utilizes a first wafer that includes a silicon substrate, an oxide layer, and at least one epitaxial layer disposed between the oxide layer and the silicon substrate. The first wafer may further include a polysilicon layer underlying the dielectric layer and a second dielectric layer between the polysilicon layer and the epitaxial layer. A second, single-crystal silicon wafer is then bonded to the oxide layer of the first wafer, such that the oxide layer and the epitaxial layer are between the first and second wafers. As such, the oxide Layer forms a buried oxide layer between the first and second wafers.

A portion of the second wafer above the buried oxide layer is then completely removed, such that a portion of the first wafer projects from beneath the second wafer. During removal of the second wafer portion, the oxide layer on the exposed portion of the first wafer may also be removed to expose the underlying epitaxial layer. Alternatively, this region of the oxide layer can be etched to serve as a mask for implanting dopants into the epitaxial layer to form the vertical power device. With the above-described configuration, the vertical power device can be formed in the epitaxial layer of the exposed portion of the first wafer, and the control circuitry, simultaneously formed in the portion of the second wafer remaining on the first wafer. The buried oxide layer between the first and second wafers then serves as dielectric isolation between the vertical power device and the control circuitry. If present, the polysilicon layer of the first wafer can be grounded so as to provide a shielding layer between the first and second wafers.

The process described above results in the upper surface of the second wafer being spaced about one micrometer or more from the upper surface of the first wafer's epitaxial layer. According to this invention, a dual-plane lithographic technique is employed to simultaneously fabricate the power device in the first wafer and the control circuitry in the second wafer. Electrical connection between the power device is achieved either by wire-bonding or metallization.

As described above, the process of this invention provides a self-protected, monolithically-integrated power device capable of contributing to improved system performance and reliability. The use of wafer-bonded SOI starting material and limiting the complexity of the process and resulting devices yields a smart power device whose process and

material costs are only slightly more than that of a conventional discrete power device. In addition to the process advantages of this invention, the starting materials for the first and second wafers can be independently specified in order to individually optimize the performances of the power device and the control circuitry. In addition, the SOI material and the buried oxide layer can be tailored for a given voltage capability and support a desired complement of devices for the control circuitry. Advantageously, both the SOI material and the buried oxide layer can be of high quality, since the buried oxide layer can be thermally grown on the first wafer and the second wafer can be single-crystal silicon.

Other objects and advantages of this invention will be better appreciated from the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other advantages of this invention will become more apparent from the following description taken in conjunction with the accompanying drawings, in which:

FIG. **1** represents a cross-sectional view of an IGBT device monolithically integrated with control circuitry in accordance with an embodiment of this invention;

FIG. **2** represents wafers employed to form the device of FIG. **1**, as they appear prior to being wafer-bonded;

FIG. **3** represents wafers employed to form a device of the type shown in FIG. **1**, but with the addition of a polysilicon shielding layer within the lower wafer in accordance with a second embodiment of this invention; and

FIG. **4** represents a cross-sectional view of an IGBT device with a polysilicon shielding layer in accordance with the second embodiment of this invention.

DETAILED DESCRIPTION OF THE INVENTION

Illustrated in FIG. **1** is a high voltage, vertical IGBT device **10** that is monolithically integrated with logic and control circuitry **12** in accordance with this invention. Though the invention will be described in terms of the IGBT device **10** and the control circuitry **12** shown in FIG. **1**, those skilled in the art will realize that the teachings of this invention are applicable to the monolithic integration of other power devices with various other control circuitries.

As illustrated, the power device **10** and circuitry **12** are formed on two separate wafers **14** and **16**, respectively. The circuitry **12** can be for the purpose of protecting the power device **10** from over-temperature, over-voltage and/or over-current conditions. As is apparent from FIG. **1**, the wafers **14** and **16** are bonded together such that the power device **10** is both monolithically integrated with and dielectrically isolated from the circuitry **12** by a buried oxide layer **18**, such that the upper wafer **16** is generally characterized as being silicon-on-insulator (SOI). In this manner, the power device **10** is formed in the lower or "handle wafer" **14** below the buried oxide layer **18**, while the control circuitry **12** is formed in the upper or "SOI wafer" **16** above the buried oxide layer **18**. Metallization **32** present on the SOI wafer **16** enables the circuitry **12** and the power device **10** to be electrically interconnected using such conventional methods as wire bonding or metallization.

As shown in FIGS. **1** and **2**, the handle wafer **14** includes a silicon substrate **20** that serves as the anode for the power device **10**, the buried oxide layer **18**, and an epitaxial layer **24** disposed between the oxide layer **18** and the substrate **20**. The substrate **20** preferably has a <100> crystallographic orientation and its characteristics are chosen to optimize the power device **10**, since the substrate **20** does not affect the circuitry **12** on the SOI wafer **16**. A suitable thickness for the substrate **20** is about 350 micrometers, and a suitable resistivity is about 0.01 ohm-centimeter. Shown in FIGS. **3** and **4** are optional polysilicon **26** and second oxide layers **22** above the oxide layer **18**. As will be explained in fuller detail, the polysilicon layer **26** when grounded can advantageously serve as a shielding layer for the circuitry **12**. For the IGBT device **10**, the substrate **20** is preferably heavily doped p-type and has an epitaxially-grown N+ buffer layer **30** over which the epitaxial layer **24** (n-type) is grown, as is generally conventional for IGBT devices. Suitable thicknesses and resistivities for the buffer layer **30** and epitaxial layer **24** are about 10 micrometers and about 0.1 ohm-centimeter, and about 70 micrometers and about 30 ohm-centimeters, respectively.

The oxide layer **18** is thermally grown to a thickness that is governed by the maximum voltage of the substrate **20** and bonding considerations, a suitable thickness being about one micrometer. If employed as shown in FIGS. **3** and **4**, the polysilicon layer **26** can be deposited to have a thickness of about 0.5 micrometers as amorphous silicon to promote the uniformity of the oxide layer **22** grown from its surface. In addition, the polysilicon layer **26** is preferably doped n-type to promote its conductivity. The oxide layer **22**, if employed as shown in FIGS. **3** and **4**, is thermally grown to a thickness governed by the maximum voltage of the circuitry **12** and bonding considerations, with a suitable thickness generally being about 0.4 micrometer.

In the context of the control circuitry **12** shown, the SOI wafer **16** is preferably a single crystal silicon wafer lightly-doped n-type to have a resistivity of about two ohm-centimeters. The SOI wafer **16** is shown in FIG. **1** as being direct wafer-bonded to the oxide layer **18** of the handle wafer **14**, such that the oxide layer **18** and the epitaxial layer **24** are between the handle and SOI wafers **14** and **16**, with the result that the oxide layer **18** forms the buried oxide layer **18** of FIG. **1**. The characteristics of the SOI wafer **16** can advantageously be chosen to optimize the operation of the circuitry **12**, since the SOI wafer **16** does not affect the operation of the power device **10** in the handle wafer **14**. After bonding, the SOI wafer **16** is etched back to achieve a desired film thickness governed by the circuitry **12**, generally on the order of about two to ten micrometers.

Processing steps for the fabrication of the power device **10** and circuitry **12** of FIG. **1** are generally as follows. The SOI wafer **16** must be etched in order to expose the surface or the handle wafer **14** in which the power device **10** is to be formed. Such an etch can be accomplished by patterning an oxide layer (not shown) on the surface of the SOI wafer **16** via a wet etch, such as an HF acid solution, and then employing the oxide layer as a mask through which the exposed portion or portions of the SOI wafer **16** are removed. TMAH (tetramethyl ammonium hydroxide) is a preferred etchant for its ability to cleanly and quickly etch silicon, and because the buried oxide layer **18** can serve as an effective etch-stop with a large tolerance for over etching. If the oxide layer **22** and polysilicon layer **26** of FIGS. **3** and **4** are present, a suitable etching technique would be to alternate HF and TMAH etches to sequentially remove these layers and expose the oxide layer **18**.

After the desired portion of the SOI wafer **16** is removed, a conventional IGBT process can be used to fabricate the power device **10** in the epitaxial layer **24** and the circuitry **12** in the remaining portion of the SOI wafer **16**. The oxide layer **18** that remains over the epitaxial layer **24** following etching of the SOI wafer **16** can be selectively etched to serve as a masking layer for predeposition of P+ regions **34** for the power device **10**, and then subsequently removed to permit further fabrication of the power device **10**. To minimize processing costs, the power device **10** and circuitry **12**

may be fabricated simultaneously and share all process features, including a field oxide **42**, gate oxides **40**, a polysilicon layer **44**, P+ sinker diffusions **34**, P-well diffusions **36**, P+diffusions **48**, N+ diffusions **50**, an interlevel dielectric **46**, and the metallization **32**. The metallization **32** may include bond pad areas to allow wire-bonding interconnections between the power device **10** and the control circuitry **12**. One skilled in the art will appreciate that a variety of junction-isolated logic devices can be conventionally formed in the SOI wafer **16** in accordance with this invention, including the NMOS, PMOS and vertical NPN bipolar transistors shown in FIG. **1**.

Key aspects of this invention include the implementation of a dual-plane lithography technique, which is necessitated by the circuitry **12** likely being located several micrometers above the surface of the handle wafer **14** in which the power device **10** is formed. While dual-plane lithography might be considered an obstacle to successful implementation of the present invention, it has been determined that the depth-of-field available using projection aligner technology is sufficient to simultaneously reproduce features on both wafers **14** and **16**. In addition, slight modifications to the process by which resist is deposited, such as a thicker resist, a faster spread speed and/or a slower spin speed, have yielded acceptable resist coverage of both wafers **14** and **16** for patterning the features of the power device **10** and circuitry **12**.

Another aspect of this invention is providing electrical interconnection between the power device **10** and its circuitry **12**. One approach is to employ wire-bonding directly between bond pads formed on the power device **10** and circuitry **12**. Such an approach is particularly attractive if only one or two interconnections between the power device **10** and the circuitry **12** are required, e.g., one for gate drive to the power device **10** and possibly one for current-sensing. Alternatively, and particularly if additional interconnections are desired, metal step coverage between the wafers **14** and **16** can be achieved using a dual-level metal technique, in which a resist, spin-on-glass, polyimide or a multilayer dielectric is used to provide a planarized die surface through which contact holes are formed for metallization. Alternatively, "stair steps" can be etched into the layers that project above the handle wafer **14**, i.e., the buried oxide layer **18**, the single-crystal silicon of the SOI wafer **16**, and its oxide layers **42** and **46**, in order to facilitate metallization.

Yet another important aspect of this invention is the isolation achieved between the power device **10** and the circuitry **12**. The influence of the substrate voltage of the power device **10** will not pose a problem for many applications since the SOI wafer **16** is relatively thick and doped n-type. Under such circumstances, an accumulation layer will form above the buried oxide layer **18** to shield the circuitry **12** from the high voltage of the substrate **20**. However, if the SOI wafer **16** is relatively thin—for example, the single-crystal silicon is thinned to about 0.5 micrometers or less for the fabrication of high-speed CMOS devices—it will generally be preferable to include the polysilicon and oxide layers **26** and **22** shown in FIGS. **3** and **4**, the former of which can be grounded to provide a shielding layer between the circuitry **12** and the power device **10**.

From the above, it is apparent that the process of this invention yields a fully-integrated monolithic structure that includes the power device **10** and its control circuitry **12**. While a high-voltage vertical IGBT power device **10** is discussed and illustrated in the Figures, those skilled in the art will appreciate that the present invention can be applied to other vertical power devices, including DMOS and MOS-controlled thyristor devices. In addition, while conventional silicon processing materials can be employed to form the power device **10** and circuitry **12**, it is foreseeable that other materials could be used, with the choice of materials determining the appropriate processes for forming selective regions of conductivity and resistance in the wafers. While the polarity of p-type and n-type regions in the wafers are generally interchangeable, each conductivity type incurs tradeoffs that would be appreciated and accommodated by one skilled in the art. Consequently, it is foreseeable that the present invention can be utilized to encompass a multitude of applications through the addition or substitution of other processing choices and technologies. Finally, there may be additional layers of passivation or protection required for manufacturability, as is known to those skilled in the art.

Therefore, while the invention has been described in terms of a preferred embodiment, it is apparent that other forms could be adopted by one skilled in the art. Accordingly, the scope of the invention is to be limited only by the following claims.

What is claimed is:

1. A semiconductor device comprising:

a first wafer comprising a silicon substrate, an epitaxial layer on the silicon substrate, a first dielectric layer on a first limited surface region of the epitaxial layer corresponding to a first surface region of the first wafer, a polysilicon layer on the first dielectric layer, and a second dielectric layer on the polysilicon layer;

a vertical power device formed in a second limited surface region of the epitaxial layer that remains exposed by the first dielectric layer, the polysilicon layer and the second dielectric layer, the second limited surface region of the epitaxial layer corresponding to a second surface region of the first wafer;

a second wafer bonded to the second dielectric layer of the first wafer such that the second surface region of the first wafer is exposed and such that the second dielectric layer, the polysilicon layer and the first dielectric layer of the first wafer are between the second wafer and the epitaxial layer of the first wafer, the second wafer having a surface that is parallel to and spaced apart from the second surface region of the first wafer in a direction substantially perpendicular to the second surface region of the first wafer; and

control circuitry formed in the surface of the second wafer and electrically connected to the vertical power device;

wherein the first dielectric layer defines a buried oxide layer between the first and second wafers so as to form dielectric insulation between the vertical power device and the control circuitry, and wherein the polysilicon layer is grounded so as to provide a shielding layer between the first and second wafers.

2. A semiconductor device as recited in claim **1** wherein the substrate of the first wafer is of a first conductivity type, the first wafer further comprising a buffer layer of a second conductivity type between the substrate and the epitaxial layer.

3. A semiconductor device as recited in claim **1** wherein the second wafer is single crystal silicon.

4. A semiconductor device as recited in claim **1** wherein the surface of the second wafer is spaced at least one micrometer from the second limited surface region of the epitaxial layer.

5. A semiconductor device as recited in claim **1** wherein the vertical power device is an insulated-gate bipolar transistor.

* * * * *